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PRECURSOR IONIZATION DUE TO PHOTOIONIZATION OF H_2 IMPURITIES IN ARGON SHOCKS

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PIBAL REPORT NO. 1033

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Aerospace Engineering and Applied Mechanics

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PRECURSOR IONIZATION DUE TO PHOTOIONIZATION OF H_2 IMPURITIES IN ARGON SHOCKS [+]

by

Daniel S. Wilson* and Samuel Lederman**

Polytechnic Institute of Brooklyn

SUMMARY

A theory was recently proposed by Wilson and Lin to explain precursor effects ahead of shock waves. An indirect test of this theory was made. Experiments were performed in a pressure driven shock tube. The driven gas was Argon and the shock Mach number was 13.2. Small amounts of H_2 (2-75μHg) were added to the Argon (2×10^3 μHg). Precursor profiles were recorded as a function of the H_2 partial pressure. These profiles are in good agreement with the theoretical calculations.

+ This research was supported under Contract Nonr 839(38) for PROJECT DEFENDER, and the Advanced Research Projects Agency under Order No. 529 through the Office of Naval Research. This paper was presented at the 20th Anniversary Meeting of the American Physical Society, Fluid Dynamics Division, Bethlehem, Pennsylvania, November 20-22, 1967.

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SECTION I

INTRODUCTION

In a recent report by Wilson and Lin[1], a theory for precursor ionization in shock tubes was presented. The theory was founded on the following experimental results obtained by Lederman and Wilson[2]:

(1) the precursor is the result of photoionization, the radiation coming from the shocked gas, and

(2) the precursor profile does not change with time in a shock fixed coordinate system.

As discussed in Ref. 1, a one-step photoionization of the Argon driven gas cannot account for the precursor. The radiation for frequencies larger than the first ionization edge frequency of Argon is effectively absorbed within a centimeter ahead of the shock. Two alternative explanations have been suggested. The first assumes a multiple-step photoionization of Argon; resonance radiation first excites the Argon driven gas, and continuum radiation completes the ionization process. The second explanation, the one recently suggested by the authors of this report[2] and others, is that the precursor is due to photoionization of impurities which are present in the Argon driven gas. The Argon provides the high temperatures behind the shock, but the radiation from this hot gas is absorbed by impurity atoms in the driven gas.

This second explanation is favored by the authors of this report for the following reasons: In the experiments of Ref. 2, the Argon driven pressure was changed from 1 mm. to 10 mm. without substantially altering the precursor profile. (The shock Mach numbers did vary but, since then, tests have been performed with different driven pressures, keeping the Mach number constant, with essentially the same result.) It is felt that if a multiple-step process in Argon were responsible for the precursor, a ten-fold increase in Argon driven pressure should at least have produced a substantially sharper drop with distance ahead of the shock in the precursor profile.

With these experimental ramifications in mind, the theory of Ref. 1 evolved. This theory can be applied to impurities in the Argon driven gas. It is necessary to know the type and amount of each impurity and absorption cross-sectional information for these impurities. An attempt is currently being made to calculate the precursor profile due to residual impurities in the Argon driven gas.

If the precursor profile were found to be sensitive to the addition of small amounts of a single impurity, an indirect test of the theory could be made. This impurity could be added in sufficient quantities so as to "swamp out" the contributions to the precursor from the residual impurities in the driven gas. By adding varying amounts of this impurity to the driven gas, the predictions of the theory could be compared with experiment.

The precursor profile was found to be very sensitive to the addition of small amount of H_2 (. - 10μHg) to the Argon driven gas. Moreover, the absorption cross-section and its behavior at the first ionization edge of H_2 is accurately known. To test the validity of the theory, therefore, experiments were performed where small amounts of H_2 were added to the driven gas. The predictions of the theory have already been set forth in Ref. 1 for an H_2 impurity (these calculations will be modified in this report) and comparisons will be made herein with experiment.

The authors would like to thank Mr. Tony C. Lin for his help with the computations.

SECTION II

THEORY

The precursor profile is calculated from the following equation[1]:

$$n(x) = \frac{An_g}{4\pi U} \left\{ \int_{\nu_i}^{\infty} \frac{N(\nu)\, Q_i(\nu)}{x} \exp\left[- \varepsilon \right] d\nu \right.$$

$$\left. + n_g \int_{\nu_i}^{\infty} N(\nu)\, Q_i(\nu)\, Q(\nu)\, Ei(- \varepsilon) d\nu \right\} \tag{1}$$

where $\xi = n_g Q(\nu) x$ and Ei is the exponential integral. The symbols in this equation represent the following:

x	distance ahead of the shock
$n(x)$	electron number density
A	cross-sectional area of shock tube
n_g	number density of absorbing impurity molecules
U	shock speed
ν_i	the frequency of the first ionization edge of the impurity particle
$N(\nu)$	the number of photons per square cm per second per unit frequency range emitted at frequency ν at $x=0$
$Q_i(\nu)$	the cross-section for ionization
$Q(\nu)$	the cross-section for absorption

In Ref. 1, this equation was applied to photoionization of H_2. The justification for using a black body source for $N(\nu)$ was presented in this report. Also, the integration was carried out from $\nu = \nu_{i_{H_2}} = \frac{15.4 \text{ ev}}{h}$ to $\nu = \infty$. If Argon is the driven gas, as is the case for the present investigation, then all photons with frequencies higher than the first ionization edge of Argon, $\nu_{iA} = \frac{15.7 \text{ ev}}{h}$, will be absorbed at the shock front and will not penetrate into the precursor region. For this reason, the calculations of Ref. 1 were repeated, integrating Eq. (1) from $\nu = \frac{15.4 \text{ ev}}{h}$ to $\nu = \frac{15.7 \text{ ev}}{h}$. Since the integration interval is small, average values of $Q(\nu) = 10^{-17}$ cm^2 and $Q_i(\nu) = 4 \times 10^{-18}$ cm^2 were used in this interval.[3] The results are plotted in Fig. 1. Notice that the same behavior in the precursor profile with varying H_2 partial pressure is still maintained, namely, an increase in the precursor level with increasing H_2 partial pressure and an eventual decrease in the precursor level as the H_2 partial pressure is further increased.

In Fig. 2, a comparison is made between the precursor profile as calculated in Ref. 1 and as calculated by the method outlined above at an H_2 partial pressure of 50μHg. The shapes of the profiles are approximately the same, although the number densities obtained by the latter method are lower by almost an order of magnitude than those obtained by the former method.

"Peak behavior" for the present calculations (Fig. 1) is illustrated in Fig. 3. The number densities are plotted as a function of H_2 partial pressure at a distance of x = 50 cm and x = 100 cm ahead of the shock. The H_2 partial pressures at which the peaks occur as a function of x will later be compared with experiment (Fig. 15).

SECTION III

EXPERIMENTAL PROCEDURE AND RESULTS

A pressure driven shock tube, described in a previous report[2], was used in this investigation. For all measurements the driver pressure was 800 psi H_2 and the driven pressure was 2 mm Argon to which prescribed amounts (from 2-75μHg.) of H_2 impurity were added. A continuous record of the shock speed was obtained, using a microwave technique described in a previous report[2]. In spite of the addition of varying amounts of H_2 impurity, the shock speed at the test station was maintained at .423 cm/μsec within about 1%. This corresponds to a temperature of about 11,000°K behind the shock.

The precursor profile was obtained using a cylindrical probe, .875 inches long and .040 inches in diameter, aligned with the flow and located along the axis of the shock tube (Fig. 4a). A bias of - 6V was applied to the probe so that the current to the probe was ionic current, and this current was determined by measuring the voltage drop across a 10K resistor connected in series (Fig. 4b). Typical scope traces are shown in Fig. 5a and Fig. 5b. The low sensitivity beam, Fig. 5a, determines the time of shock arrival at the probe, while the high sensitivity beam, Fig. 5b, gives the precursor distribution ahead of the shock.

To convert ion saturation currents into ion number densities, the probe was calibrated using a microwave flow-through cavity[2]. For each H_2 partial pressure a single cavity resonance was recorded (Fig. 5c). This determines the number density for one distance ahead of the shock. The number density as a function of x is then obtained by assuming a proportionality between ion saturation current and ion number density.

The raw data is plotted in Fig. 6. The ion saturation current is plotted as a function of distance ahead of the shock. The amount of H_2 impurity added to the Argon driven gas appears as a parameter. The precursor densities increase with increasing H_2 partial pressure and then begin to decrease as the partial pressure is further increased - the same behavior that is predicted by the theory.

The curves in Fig. 7 illustrate this "peak behavior". The number densities are plotted as a function of H_2 partial pressure for two fixed distances ahead of the shock (50 and 100 cm). The large uncertainties in the H_2 partial pressures at which the peaks occur lead to large "error bars" on the experimental points in Fig. 15, where the theory is compared with the experiment.

SECTION IV

COMPARISON OF THEORY AND EXPERIMENT

In Figs. 8 thru 14, the experimental profiles are compared with theory. Each figure is for a different H_2 partial pressure. The microwave measurement for each H_2 partial pressure is indicated by a circle. At all pressures the shape of the profiles predicted by the theory is in fairly good agreement with the experimental profile shape. This will be further discussed below (Fig. 16).

The number densities given by theory and experiment are in better agreement at the higher H_2 partial pressures. In fact, the discrepancies between theory and experiment increase as the H_2 partial pressure decreases (at a partial pressure of 2μHg, the experimental number densities are more than an order of magnitude higher

than the theoretical values). For all partial pressures the experimental values are higher than the theory predicts. It is felt that the reason for the higher experimental values is that the assumption of no reflection of the radiation by the shock tube walls[1] is not entirely valid. Even at these high U.V. frequencies enough radiation is reflected back into the shock tube to explain the discrepancies. This has been experimentally verified by measuring the precursor ahead of the shock in a large dump tank where the walls have been removed.[4]

There is no clear-cut explanation for the larger discrepancies at the lower H_2 partial pressures. It is very likely connected with the fact that the contributions to the precursor from other impurities are more evident when less H_2 is added to the driven gas. At least this explanation is consistent with larger experimental than theoretical values of number density.

In Fig. 13, (H_2 partial pressure is 50μHg) the precursor profile obtained from Wetzel's theory[5], applied to photoionization of H_2, is plotted for comparison. The number densities for the Wetzel curve are several orders of magnitude higher than the experimental measurements, and the "fall-off" with distance ahead of the shock is not as fast as the experiment indicates.

In Fig. 15, a comparison is made of the theoretical and experimental values of H_2 partial pressure at which the peak value in the precursor number density occurs (as a function of distance ahead of the shock). These values of partial pressure are obtained from curves such as those plotted in Figs. 3 and 7. The agreement between theory and experiment is about as good as can be expected.

The precursor profiles, both experimental and theoretical, exhibit exponential decay far from the shock front. In Fig. 16, the slopes at a distance of x = 100 cm. are compared. The slopes are obtained directly from Figs. 8 thru 14. The theory accurately predicts the "profile shape" for all H_2 partial pressures.

It should be mentioned that such factors as black body efficiency, reflection of radiation from the walls of the shock tube, values one chooses for $Q(\nu)$, $Q_i(\nu)$, etc., affect the absolute values one obtains for precursor number densities, but the shape of the profile itself is not very sensitive to these factors. A more important criterion for the efficacy of the theory is, therefore, how well it predicts the profile shape and general qualitative features of the profile behavior with changing impurity concentrations, rather than how well it predicts the absolute number density levels, provided, of course, that the values are not too far off.

SECTION V

CONCLUDING REMARKS

The main objective of the H_2 experiments was to test the validity of the impurity photoionization theory proposed in Ref. 1. The good qualitative and quantitative agreement between the theory and the experiments justifies increased confidence in the use of this theory for calculating precursor profiles under different operating conditions.

One such application might very well be to determine the precursor distribution ahead of a reentry vehicle as a function of height, vehicle attitude and velocity, etc. Since the composition of the atmosphere as a function of height is fairly well established, it should be possible to make this type of calculation.

Further experiments are planned to determine the types of ions and the number densities of each type in the precursor region. This kind of information would prove invaluable in tying together all aspects of the precursor problem.

SECTION VI

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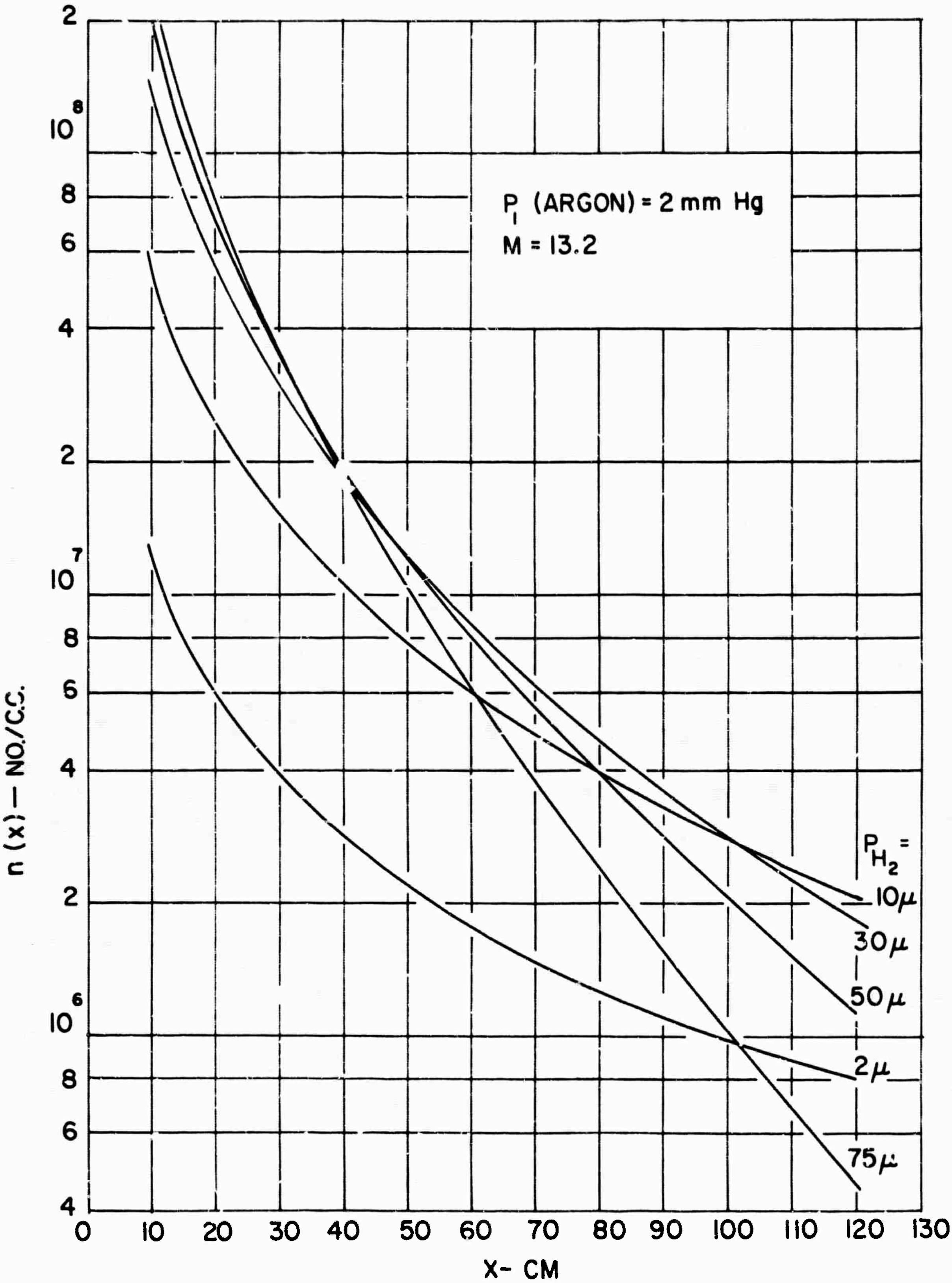


FIG. 1 THEORETICAL DEPENDENCE OF PRECURSOR PROFILE ON MOLECULAR HYDROGEN PARTIAL PRESSURE

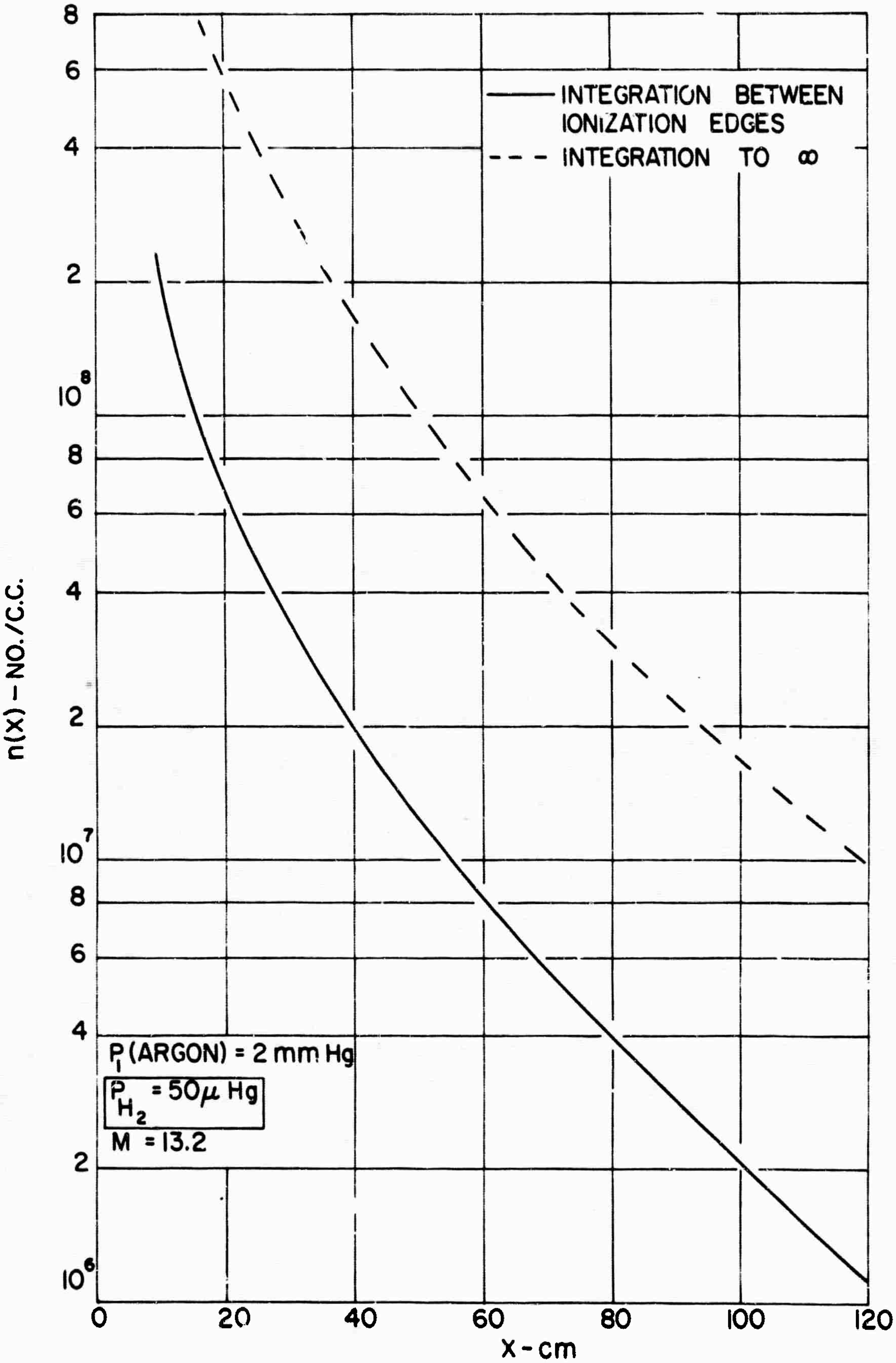


FIG. 2 THEORETICAL 1D PRECURSOR PROFILES

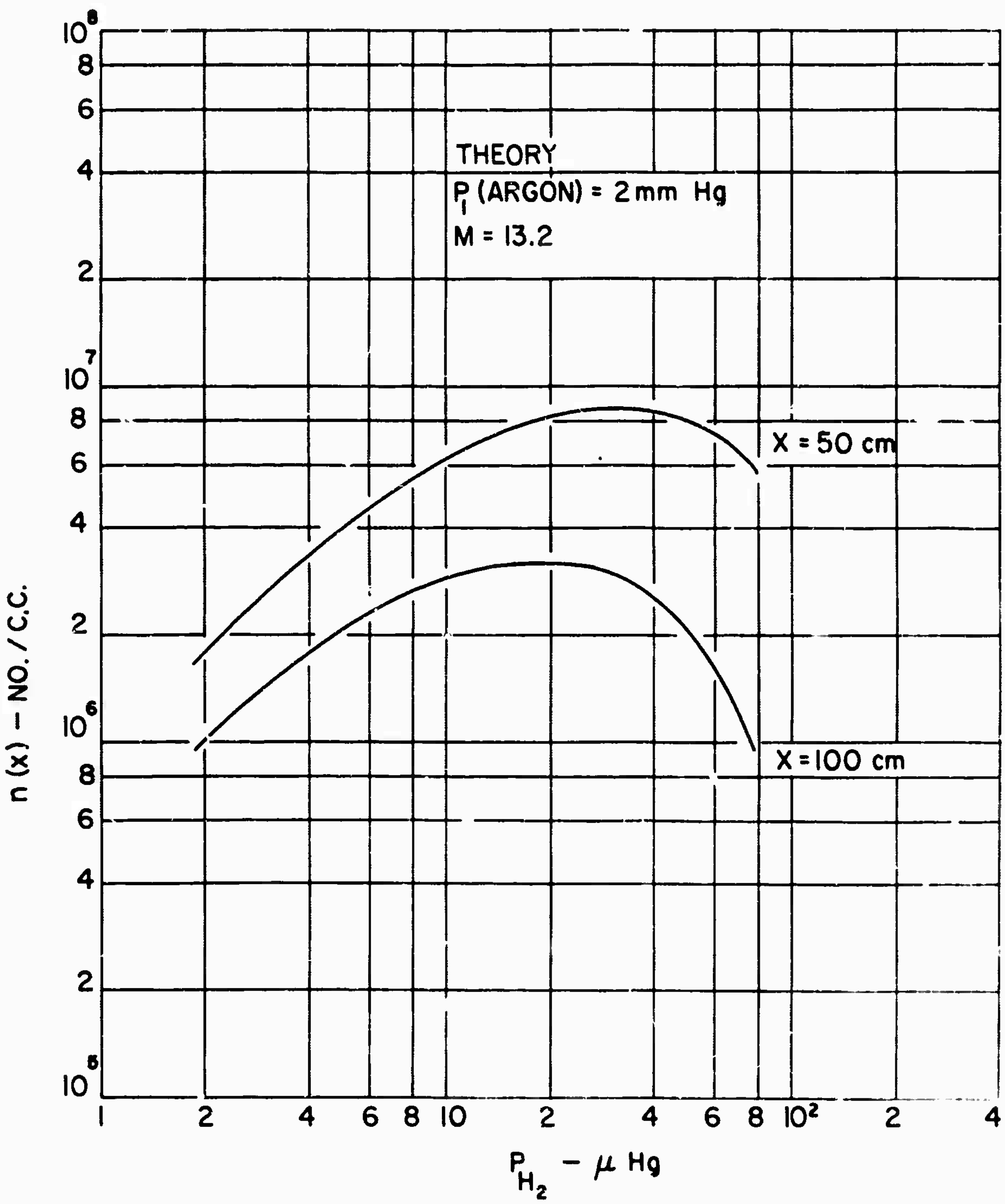
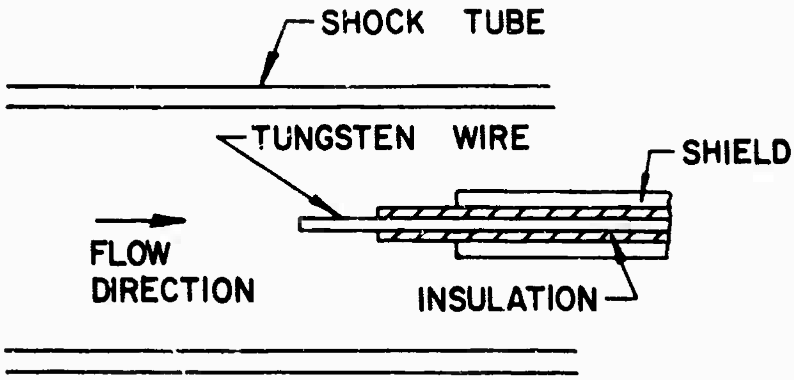
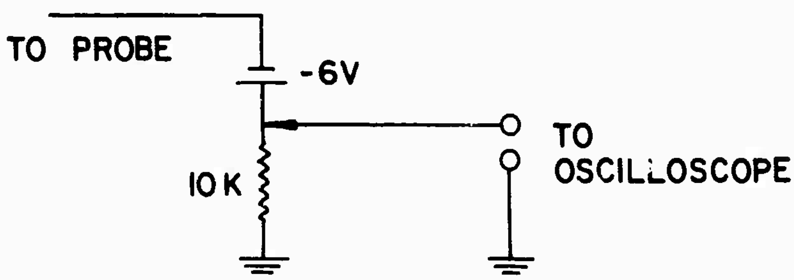


FIG. 3 PRECURSOR NUMBER DENSITY VS. H_2 PARTIAL PRESSURE



4a location of probe in shock tube
(not to scale)



4b probe circuit

FIG. 4 ELECTROSTATIC PROBE AND CIRCUIT

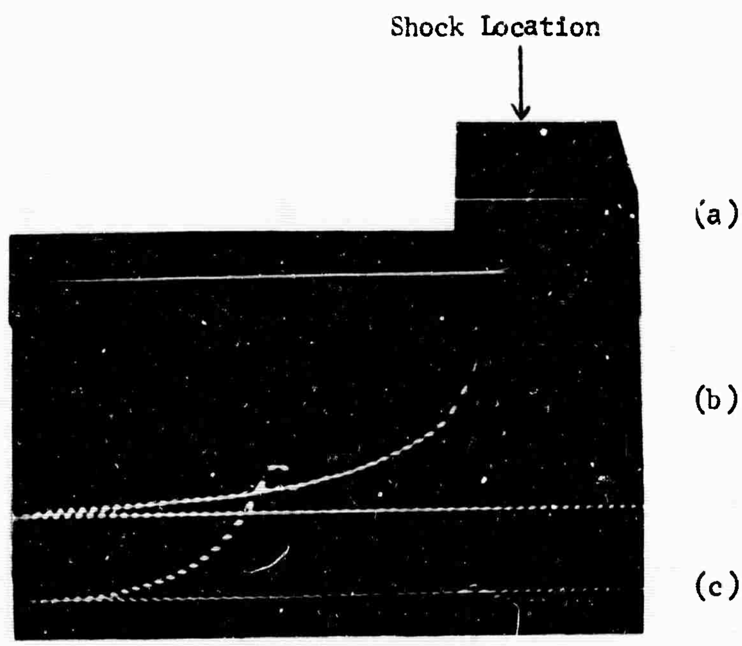


Fig. 5 Typical Experimental Traces

(a) Low Sensitivity Electrostatic Probe Trace
BIAS = -6V, 2V/DIV.

(b) High Sensitivity Electrostatic Probe Trace
BIAS = -6V, 50 MV/DIV.

(c) S-Band Cavity Response

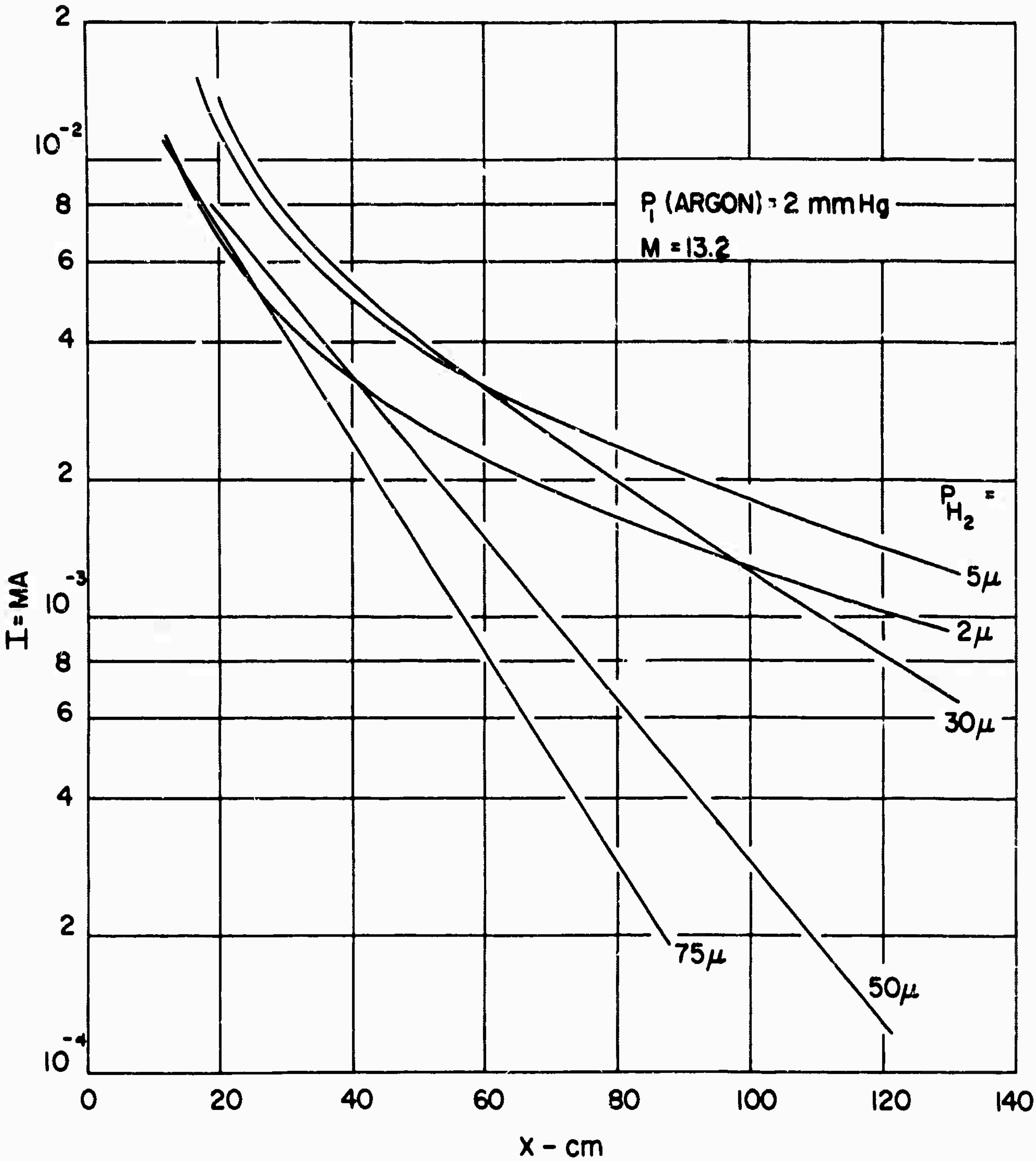


FIG. 6 EXPERIMENTAL DEPENDENCE OF PRECURSOR PROFILE ON MOLECULAR HYDROGEN PARTIAL PRESSURE

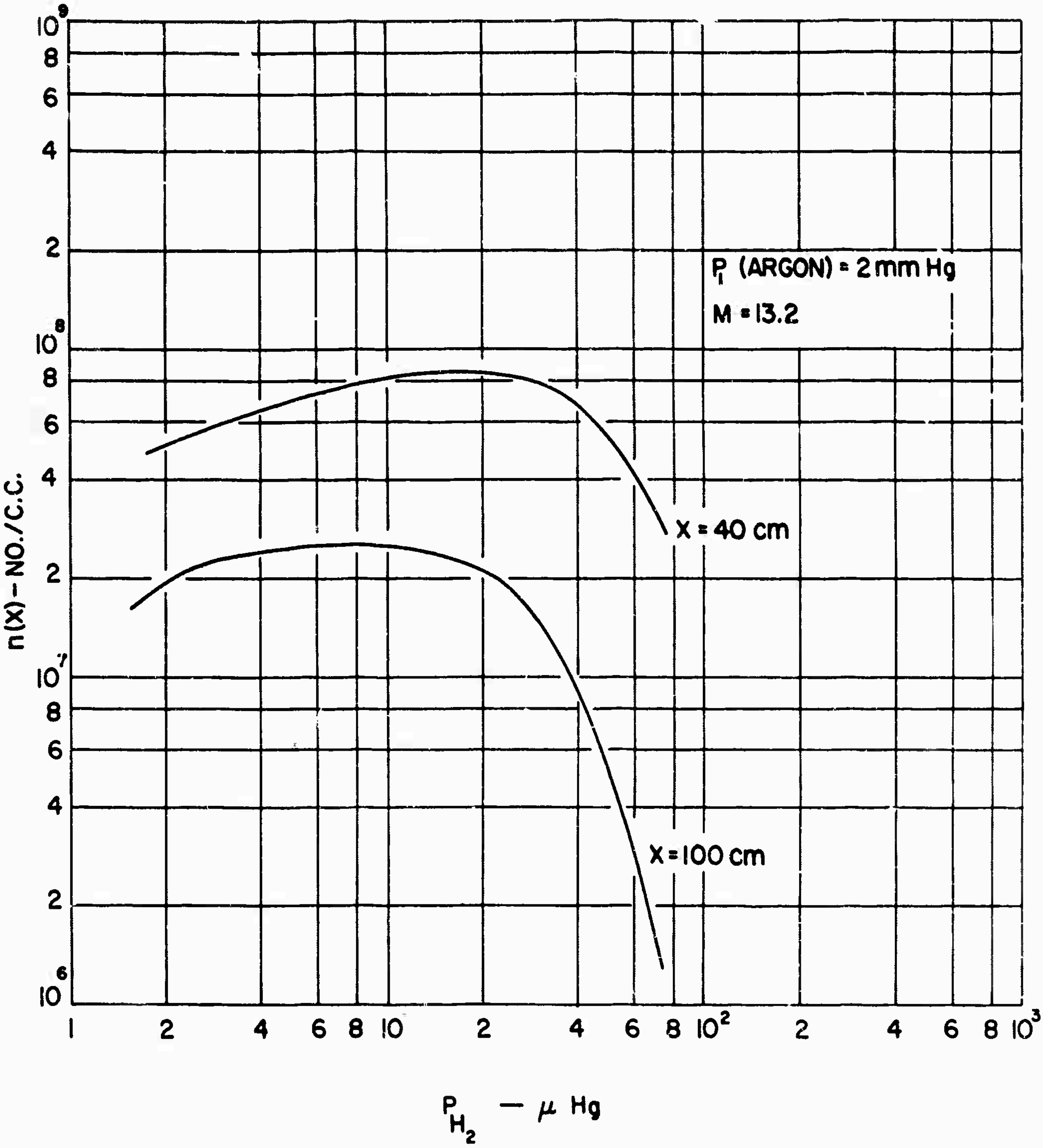


FIG. 7 PRECURSOR NUMBER DENSITY VS. H_2 PARTIAL PRESSURE - EXPERIMENT

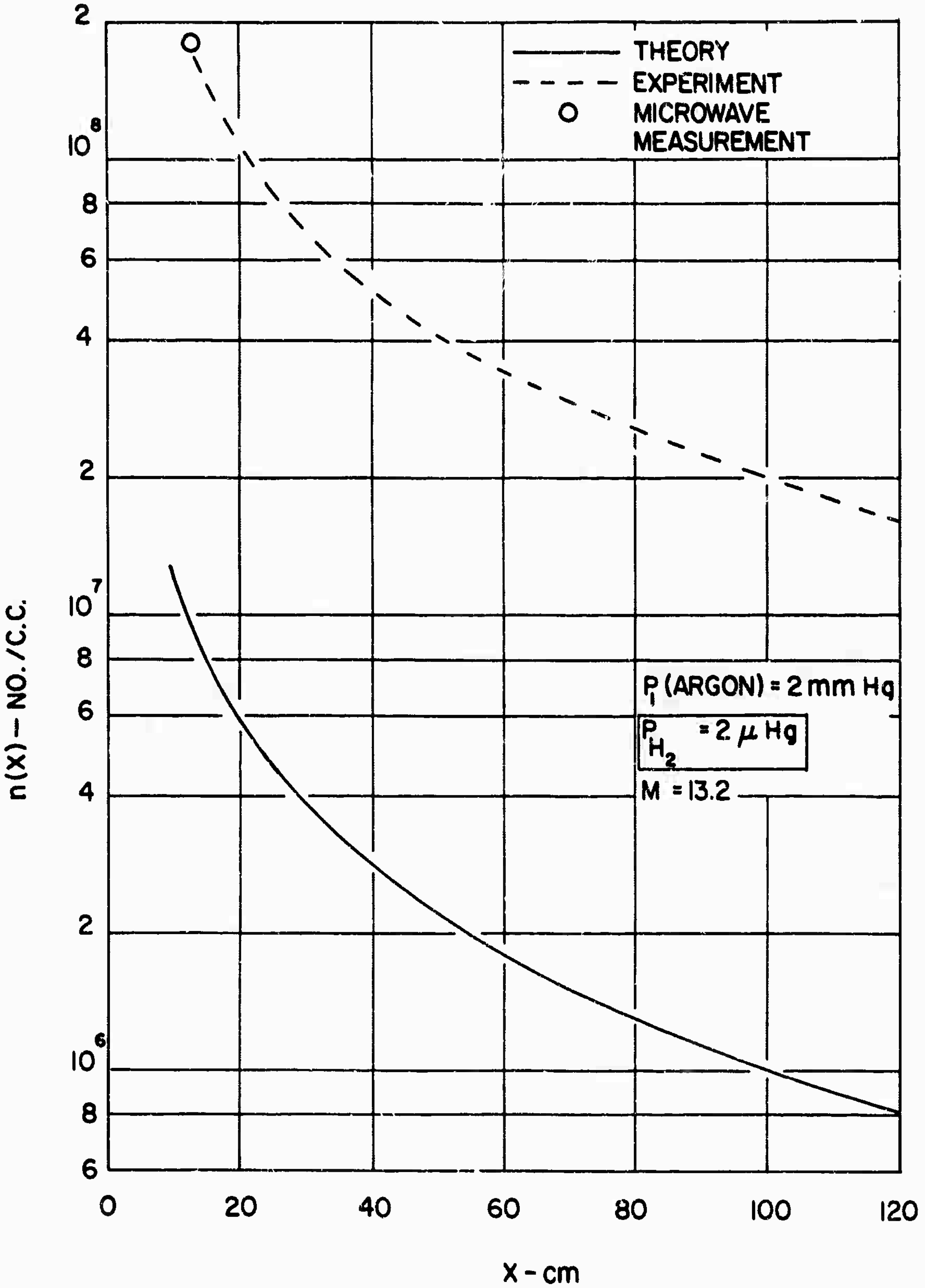


FIG. 8 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK — I

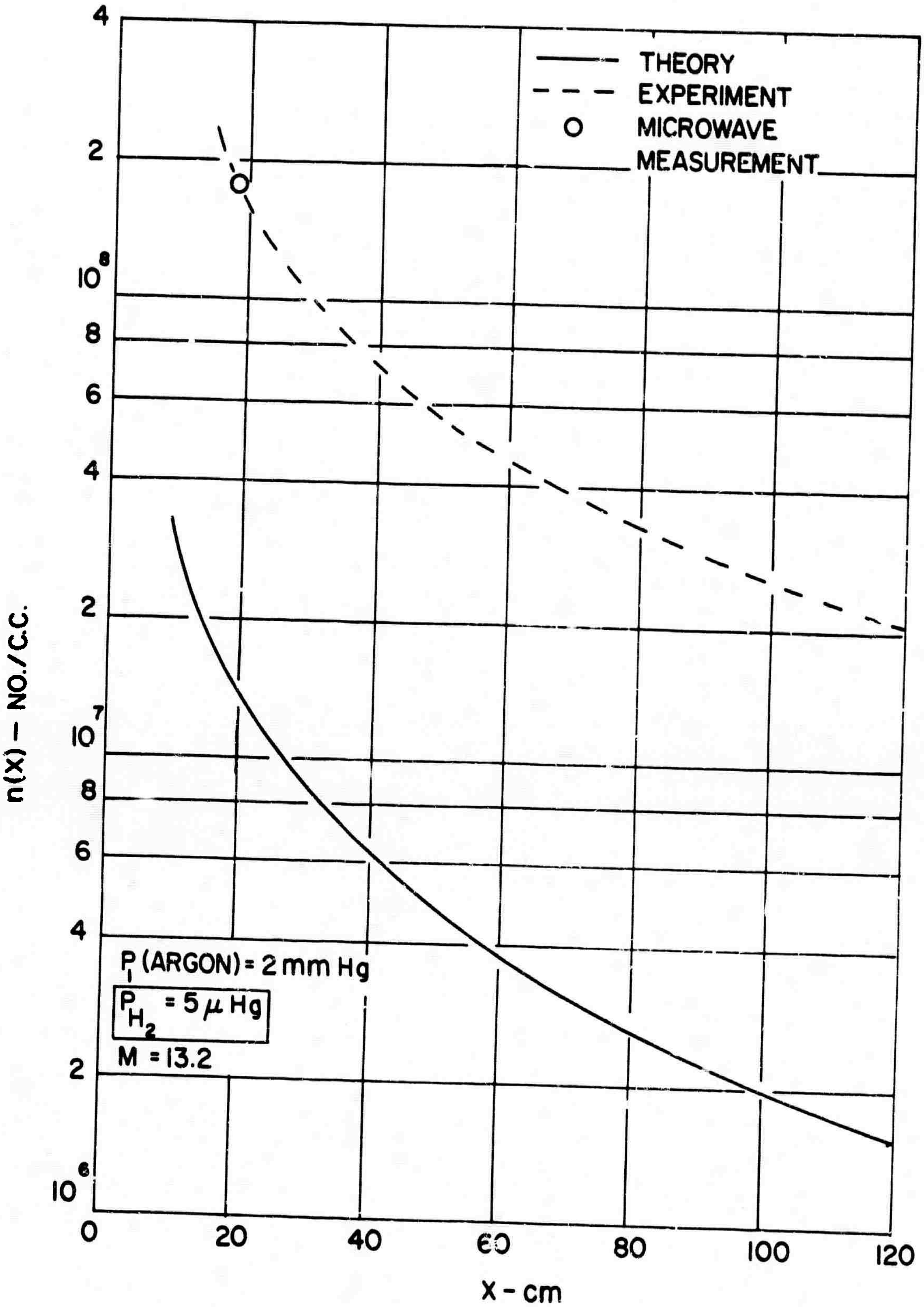


FIG. 9 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK – II

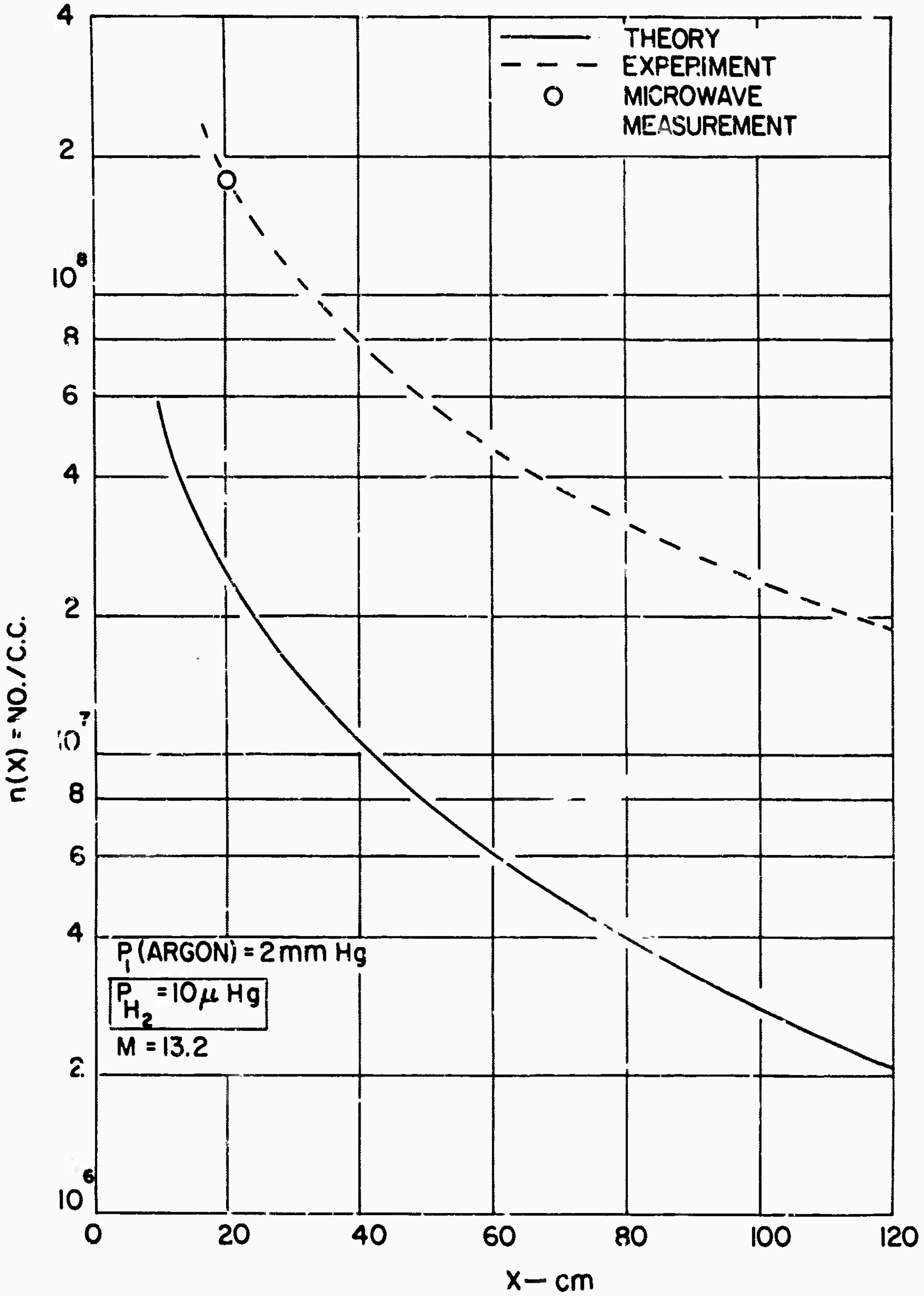


FIG. 10 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK — III

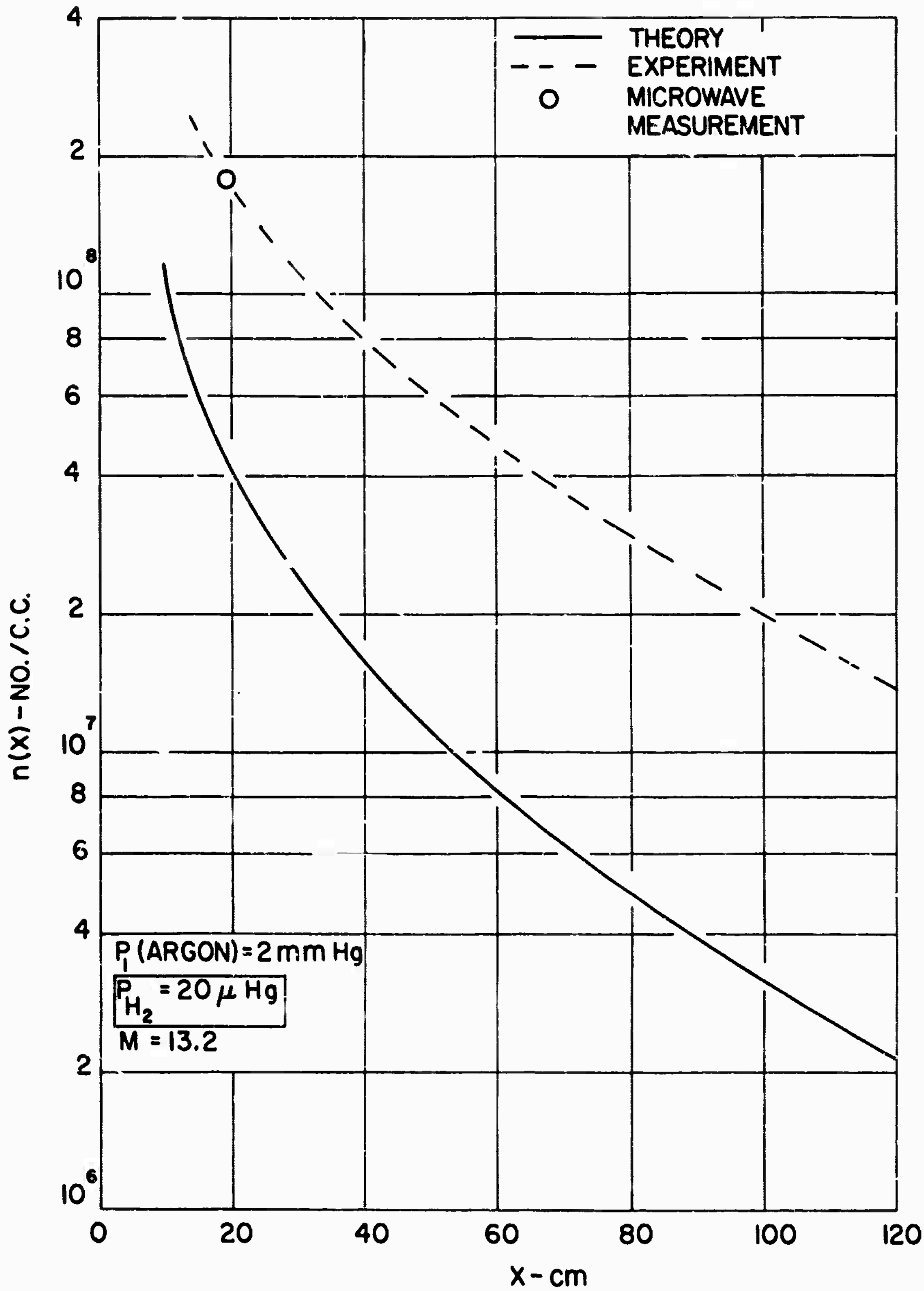


FIG. 11 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK — IV

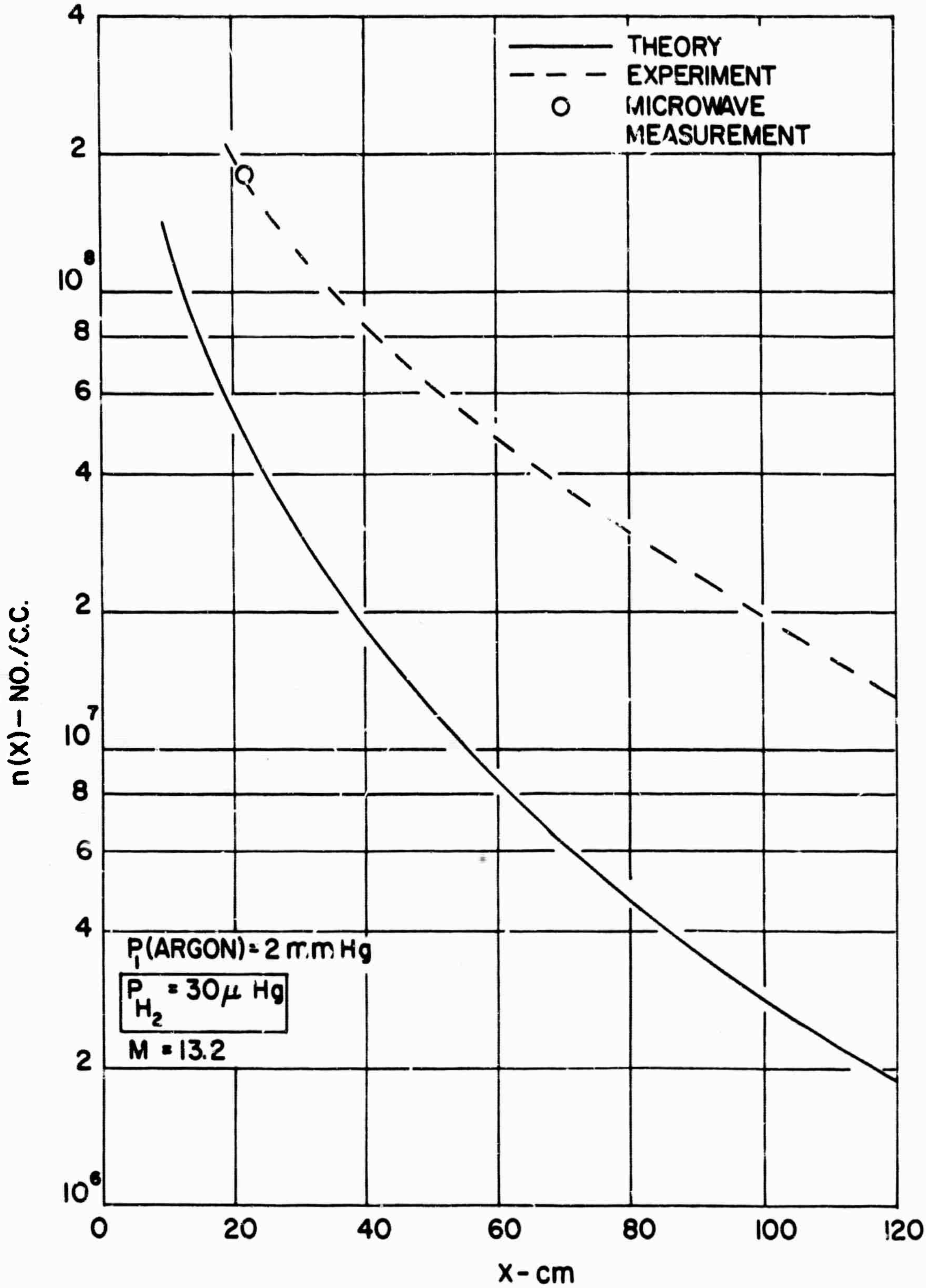


FIG. 12 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK – V

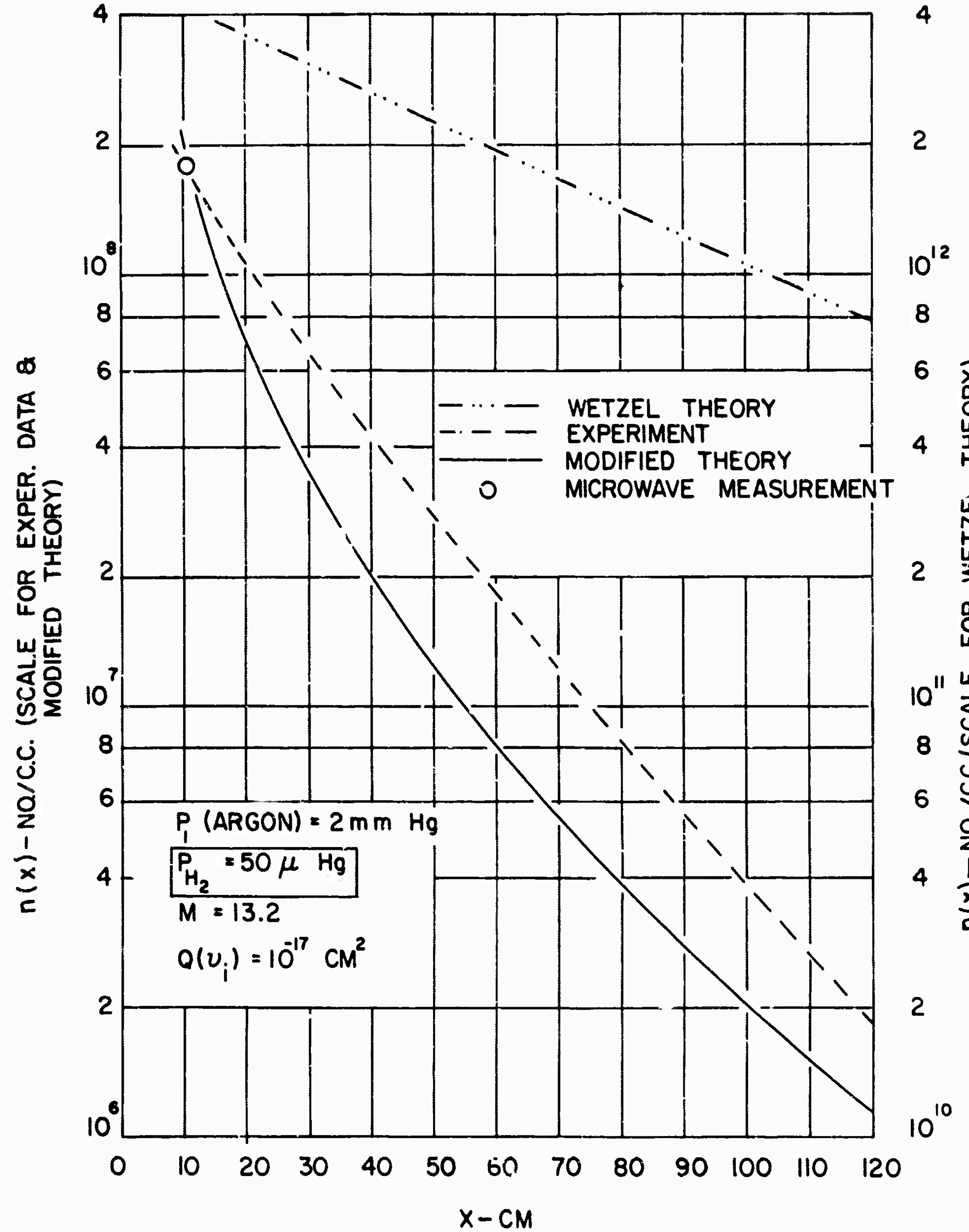


FIG. 13 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK - VI

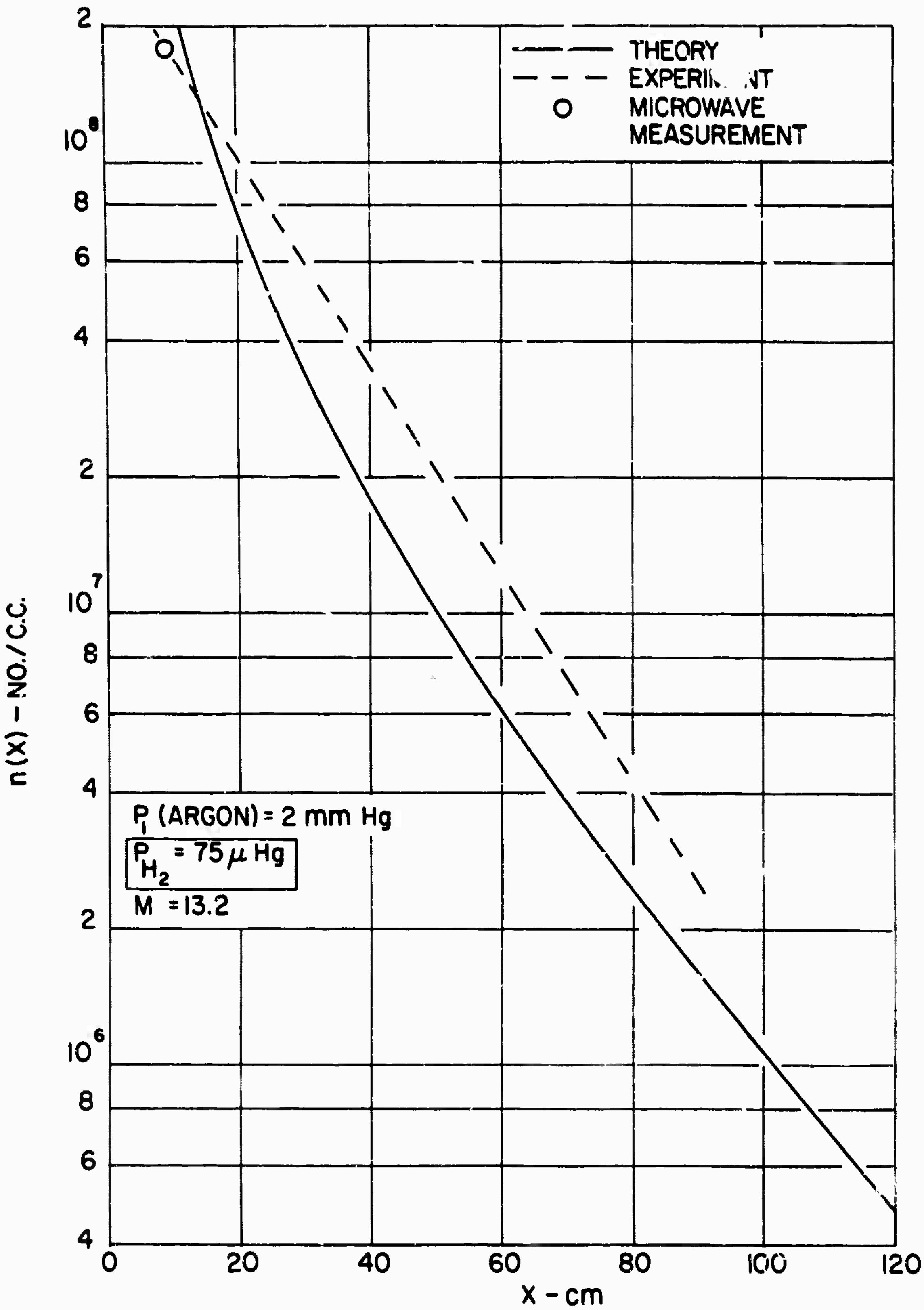


FIG. 14 PRECURSOR NUMBER DENSITY VS. DISTANCE IN FRONT OF SHOCK – VII

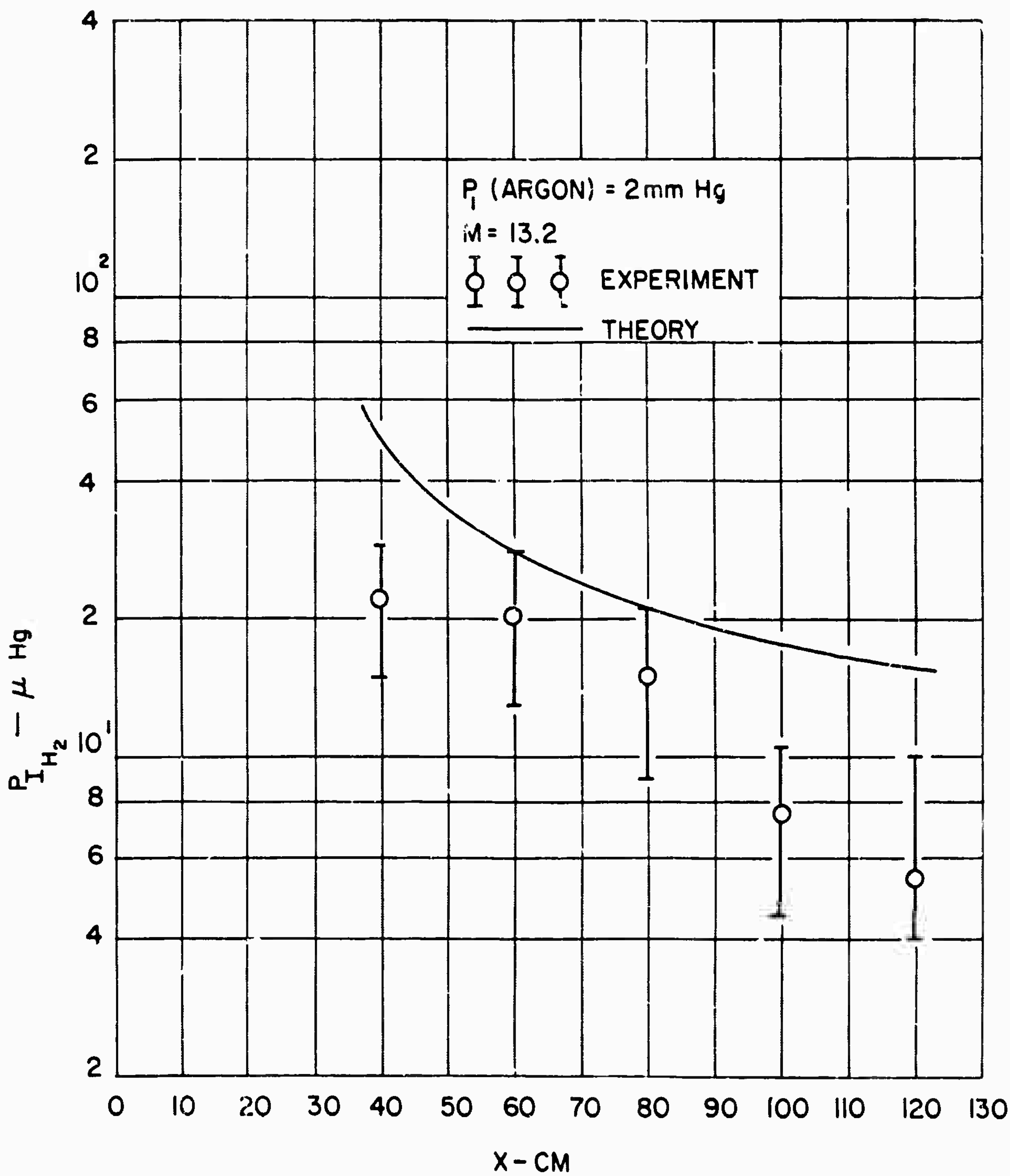


FIG. 15 PARTIAL PRESSURE OF H_2 FOR PEAK PRECURSOR DENSITY VS. DISTANCE IN FRONT OF SHOCK

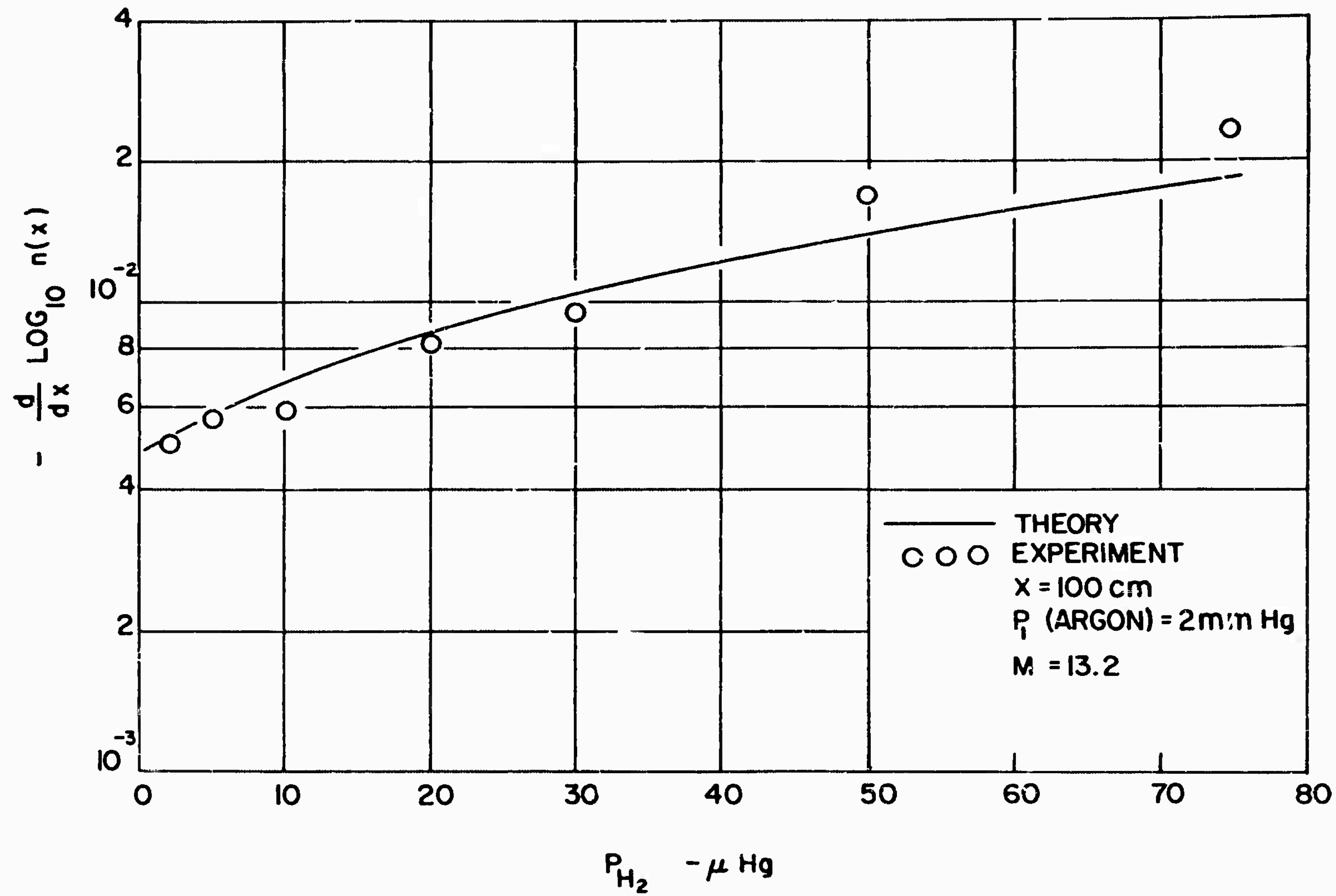


FIG. 16 SLOPES OF PRECURSOR PROFILES VS. H_2 PARTIAL PRESSURE

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13. ABSTRACT

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Shock Tubes						
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Photoionization						